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ANALYSIS OF EROSION-RELATED FAILURE INFORMATION FROM COAL GASIFICATION SYSTEMS

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ABSTRACT

Failure information reports concerning erosion that are contained in the NBS-DOE Failure Information Center have been analyzed for the purpose of identifying critical gasification applications. Emphasis was placed on the components most frequently identified in erosion failure reports - piping, valves, pumps, cyclones - and on three of the principal processes. Recommendations are presented on a minimum set of erosion-related information needed to analyze erosion behavior. A brief review of solid particle erosion and several bibliographic references are also included.

INTRODUCTION

The erosion of materials by surface impact of hard particles is one form of material wear. It is understood that wear is, in general, a complex phenomenon, consisting of simultaneous and interacting processes involving mechanical and chemical effects as well as material parameters. In recent years considerable progress has been made in gaining an appreciation of the significant parameters of erosion and wear and in applying a materials methodology to the problem. Technological improvements in erosion-resistant performance of products should be possible now. It is well to keep in mind that other wear processes, e.g., abrasive wear and corrosive wear, involve many similar characteristics and perhaps mechanisms with erosion. Progress in understanding any one of these processes may be applicable to the development of more erosion resistant materials and systems.

This report will examine the problem of erosion-related failures of components in coal gasification systems. It is hoped that an evaluation of the existing data and information will assist in identifying common, significant problems and solutions among different facilities and to some extent among different system components. Emphasis will be placed on the components most frequently identified in erosion failure reports and on three of the coal gasification systems; Hygas, Synthane, and CO_2 Acceptor processes.

A brief summary of particulate erosion will be given first in order to indicate the significance of the many factors involved. This summary should assist in assessing the erosion/corrosion problems reported in connection with coal gasification equipment. Several reviews of solid particle erosion have appeared recently.[1-4] The state of earlier understanding has been adequately reviewed in several additional articles[5-8] which also can be consulted. While these reviews emphasize basic erosion processes, many examples are provided

therein of practical problems (see ref. 1).

II. Particulate Erosion of Materials

Technological concern with the erosion of materials involves steady state long term erosion.[9] Consideration of the effects of a flux of particles incident on a surface for some length of time suggests that many complex aspects are present. These include a wide range of simultaneous attack angles, particle fragmentation, surface shielding due to deposits, particle embedding and particle/surface reaction effects, among others, all in addition to the basic process of erosion impact.

Two basic types of equipment have been used in the laboratory to expose solid specimens to a stream of erosive particles for the purpose of obtaining erosion data on materials. In one design the specimen is moved at a controllable velocity, usually on a rotating arm fixture, through a slowly moving erosive stream. The exposure may be intermittent but can continue for a long time period. The relative particle-specimen velocity can be accurately determined since the principal velocity component is that of the specimen (in the laboratory system). A variation on this design allows the erosive particles to be spun from a rotating disk to strike a fixed specimen. The alternative design involves propelling a stream of particles at a fixed specimen. The specimen may be completely immersed in the stream, or perhaps only a portion of the specimen exposed. In this scheme some method of measuring or calculating particle velocity must be used. The particle concentration in the stream and the nature of the carrier gas (fluid) can be chosen. Some type of nozzle or flight tube is involved in order to properly confine the erosive stream.[10-12]

Quantitative measurements of erosion rate require careful attention to the experimental system and the parameters of exposure. For example, wear of the abrasive delivery nozzle can greatly alter the stream shape and velocity profile. Turbulance within a flight tube or caused by the presence of the specimen itself in the stream can significantly affect particle flux and particle velocity as experienced by the test specimen, particularly for small particle sizes. Consideration of the particle trajectories within the incident stream, particularly near the specimen, are important.[13] Since the erosion rate can vary as high as the third power of the particle velocity, accurate knowledge of particle impact velocity is essential. All these considerations are essential if the laboratory data are to be useful to designers of practical systems.

The variation of erosion, usually measured in mass or volume loss from the specimen per unit mass of impacting abrasive, as a function of angle of attack of the particles is shown schematically in Fig. 1 for brittle and for ductile materials. For ductile materials the peak erosion loss occurs at around 20°. For brittle materials the peak erosion loss occurs at around 90° (normal incidence). Thus, designers should avoid these erosion angles for the materials involved. The dependence of erosion rate on particle velocity has been measured for many materials over typically two or three orders of magnitude in velocity. The erosion rate is found to increase as v^2 to v^3 in most cases.[6,14] The velocity exponent has been reported not to depend on the type of material (Fig. 2); however, detailed studies have shown some dependence of the velocity exponent on the temperature of erosion (Fig. 3). A reduction in particle or flow velocity can drastically reduce erosion rate and may be the most effective design approach.

The dependence of erosion on particle size has also been studied by several workers. Goodwin *et al.*[15] have examined the erosion of steel by quartz particles over a large size range. As shown in Fig. 4, an increase in erosion with increasing particle size was found up to a limiting size, above which the erosion remained constant and then increased for particle sizes greater than about 500μm. A theory explaining this result has been proposed.[16] Much interest has been centered on the erosion effects of very small particles e.g., less than 5μm in diameter. There have been conflicting reports in the literature for such small particles. Recent studies, however, have shown significant erosion of metals by particles as small as 2μm.[17] The effect of particle size as measured using flat test specimens may not be applicable in all geometries as shown by the recent work of Mills and Mason.[18] In studying erosion in 90° tube bends due to the conveying of abrasive sands, they reported that depth of penetration for 70μm particles was much greater than for 230μm particles. Further a different surface morphology resulted and a different angle of maximum penetration was found.

The effects of increasing temperature on erosion have been studied in more detail in the last few years. The environment in which high temperature erosion takes place usually has a significant effect on erosion rate. Depending on the material being eroded, the temperature range, and the environment, different effects due to temperature have been reported. The results in one instance[10] revealed a large increase in erosion of type 310 stainless steel on going from 25°C to 975°C. A recent study[4] of erosion of aluminum and type 310 stainless steel also reported increased erosion for increased temperature. In work on other alloys, however, decreases in erosion with increasing temperature have been reported.[18] It is believed that temperature effects must be studied using the specific exposure conditions expected in the application.

One material parameter that has been of particular interest in connection with the understanding of ductile material erosion is indentation hardness. Numerous correlation studies have been attempted to determine the relation of hardness to erosion rate. In Fig. 5 some results[6] are shown. There the erosion rate of different metals decreases with increasing value of material hardness. However, the effect of hardness variation for one alloy (varied through thermal treatments of a tool steel) was found to produce little effect on erosion rate. The influence of other erosion parameters such as particle concentration in the erosive stream, particle hardness, and particle strength, have only been examined in a few instances. In the case of particle concentration, divergent findings have been reported.[20] It would seem that relative erosion (specimen mass loss divided by impacting erosive mass) should be independent of particle concentration so long as each particle event is equally effective. At higher concentrations, where particle interference (shielding) effects occur at the specimen surface, the relative erosion should be expected to decrease and this has been reported.[10,20] At elevated temperatures, the hot hardness and high temperature toughness of both the specimen and the eroding materials would be important parameters to consider.

In ceramic materials the main parameter that controls the rate of erosion is the particle velocity. A number of studies indicate that the erosion rate can be expressed as a power function of the particle velocity. As with metals, velocity exponents generally range[21,22] from $\sim$2 to $\sim$3. Higher values have been reported. The value obtained for the velocity exponent of a given ceramic material apparently bears little relation to composition or microstructure of that material. Thus, castable refractories, which are $\sim$30 percent porous and

have a multiphase structure, exhibit the same range of velocity exponents (2.3 to 3.9) as dense, relatively homogeneous ceramics such as hot-pressed silicon nitride, and high-density aluminum oxide. In dense ceramic materials, grain size also has little apparent effect on the velocity exponent, even though it has a significant influence on the absolute rate of erosion.

Brittle ceramic materials exhibit a maximum in erosion rate at an angle of 90^{o} (Fig. 6). This type of behavior has been used to classify materials as either brittle or ductile with regard to erosion. Actually, most ceramic materials exhibit behavior that is neither completely ductile nor completely brittle.

In a study of the effect of temperature on erosion, Hockey et al.,[21] demonstrated that plastic flow occurs during the erosion of brittle materials. The erosion rate of glass, silicon nitride, and aluminum oxide was measured as a function of temperature and impingement angle using ∿150μm silicon carbide particles as the erosion agent. Although a low angle maximum in the erosion rate characteristic of ductile materials was not observed, there did seem to be a significant enhancement of the erosion rate at low angles of impingement. It was concluded that wear generally occurs by a mixed mode of erosion, with the ductile processes becoming increasingly more important with decreasing angle of impingement.

Theories have been developed for the erosion rates of both ductile and brittle materials. In 1960 Finnie considered a micro-machining mechanism as a model[5] for ductile materials. He determined the erosion rate (W) to be dependent on the flow stress σ_f as follows:

$$W = \frac{mV_o^2}{\sigma_f K d}\, g\ (\alpha)$$

where m is the particle mass, V_o the impact velocity, K the ratio of vertical

force to horizontal force on the particle, and d the depth of cut. $g(\alpha)$ is a function describing the effect of attack angle α. This approach was quite successful in explaining many features of solid particle erosion. Recent refinements[4] of the original analysis have led to velocity exponents of about 2.5, which are more closely those found by experiment. Several other theories have been proposed, and recent reviews can be consulted for details.[1]

Two basic models of erosion have been developed for brittle materials: one is based on the assumption that erosion occurs entirely by crack propagation and chipping[24]; the other is based on the asumption that plastic deformation contributes to the process of crack formation and surface chipping.[25] Erosion rates are predicted in terms of both target (fracture toughness, hardness, flaw density, etc.) and particle (velocity, density, size, etc.) properties. The models assume that particle impact is normal to the target surface. The model proposed by Sheldon and Finnie[24] gives the erosion rate, W, in terms of the particle size, r, the particle velocity, V_o, and two constants, a and b:

$$W = k_1 \, r^a V_o^b$$

The erosion model developed by Evans _et al._[25] assumes that the erosion rate is proportional to the amount of material removed by each impact event. The erosion rate (W) is given by:

$$W \propto V_o^{19/6} \, r^{11/3} \, \rho^{19/12} K_c^{-4/3} \, H^{-1/4}$$

where ρ is the density, K_c the stress intensity factor, and H the hardness. Although the erosion theories summarized above are supported to some extent by erosion data from the various laboratory studies, the functional dependence of these theories on material properties differ significantly. Additional experimental testing is still required to clarify some uncertainties.

A recent conference on corrosion and erosion of materials for coal conversion applications included several papers addressing specific problems of erosion in laboratory studies as well as practical applications. The proceedings[26] of that conference provides a very valuable source of information in this field.

III. Failure Report Trends

The NBS/DOE Failure Information System receives and evaluates failure reports from field installations that identify many specific causes for the failure problems. The emphasis in this report will be on failures classified as erosion. Table I summarizes the distribution of failure causes reported through December, 1978. It is seen that erosion accounts for about 21% of all failures reported, and that same proportion is experienced at two specific gasification facilities, the Synthane facility and the Hygas facility. In view of the nature of this process; namely, the processing of coal particles, steam and gases at elevated temperatures, pressures and flow rates, it is not unexpected that solid particle erosion constitutes one of the principal, life-limiting processes for the equipment involved. Further analysis of the failure information data base provides the results in Table II concerning the components involved in erosion failures. It is seen that three principal classes of components, pumps, valves and piping, account for about 90% of reported erosion-related failures. On this basis it should be useful to carefully examine the erosio reports on those classes to identify common problems in materials, design and operation. Further, concentration of this analysis on three gasification systems; Synthane, Hygas, and CO_2 Acceptor, is also indicated since these failure reports account for (1) 55% of all reported failures, (2) 53% of all erosion failures reported, and (3) 50% of erosion reports on pumps, valves and

piping. Records for those systems seem the most detailed.

The scope of this report will be limited to the erosion failures reported for those three processes. Emphasis will be placed on the three classes of components identified above. It is thought that conclusions from this study can properly be extended to other systems and components using similar considerations. The NBS Failure Information System has the available details on all reported failures and can provide the resources needed for any additional study.

IV. Erosion Failure Information

A. Synthane Facility[27,28]

1. Piping

The Failure Information System contains 10 reports concerned with erosion-related failures of piping components. The summary of that information is shown in Table III (using a format that will be followed in this report). The basic information taken from the failure report concerned with each component is shown. Information concerned with erosion parameters such as erosion velocity, erosion depth, temperature, etc., are also listed where available.

The piping failures due to erosion involved both plain carbon steel material as well as stainless steel (304, 316). Two nickel-based alloys, I800 and I825,* were also involved in two instances. Temperatures of service ranged from 300 to 900°F depending on the location of the component. The local environment involved either coal dust or coal char as the particulate material, carried in water, steam, coal gas or other gases, or a mixture of these. Unfortunately little information was provided on the solids concentration and the erosion velocity, both of which are controlling of erosion rate. Six

*I800 (Incoloy 800); I825 (Incoloy 825)

of the components experienced erosion penetration through the wall thickness in the region where the directed flow of steam, particulates, and gases impacted the surface. Several sketches provided in the reports indicated that erosion was maximum at a low angle impact, consistant with the peak erosion angle of 20-30° usually found for metals. Several actions to reduce this erosion problem were carried out. These included redesign of the flow, the use of a blocked tee in place of an elbow (so the incident stream impacts principally on a deposit of coal or char), reduction of flow velocity, addition of wear pads to critical locations by welding, and in one case substitution of a ceramic sleeve for the original metal sleeve. One report concerned the internal cyclone used to remove fines from the gas prior to water scrubbing. As in other piping problems, the directed gas/particle flow eroded the wall of the impact site. A wear plate was installed to provide greater material thickness at the impact site.

It is difficult to draw conclusions concerning the comparative erosion rates of these piping components since in all cases essential data are missing. Measurements of erosion depth were only reported in three cases. Even in those cases, the time in service under erosion conditions was not clearly given. Further, the solids concentration and flow velocity were not provided in these reports (with one exception). Since erosion loss is generally proportional to amount of impacting solids and to the square or cube power of flow velocity, in the absence of those data it is not possible to quantitatively compare the three cases. Future failure analysis report activities should emphasize the need to obtain such data from field service.

2. Valves

There were 12 reports concerning valve failures in this group. In most cases (see Table III)the materials involved were specialty steels and alloys

indicating the recognition of the difficult service expected. Most of the valves were in pressure letdown service, with pressure drops of 600 psi to 1000 psi. The failures generally involved erosion of valve seats and internal liners designed to properly direct the flow down the piping axis. Three of the reports concerned Willis choke valve designs utilizing ceramic or tungsten carbide orifice plates. These hard materials were not sufficiently resistant to particulate erosion under the conditions present. In other reports, there was indication that solids became lodged at the valve seats preventing complete closure. The continuing leak of gases and particulates through the gap would quickly produce considerable erosion. Reaction to several of the failures involved replacement of metal parts with harder materials, such as tungsten carbide. However, it was not clear from the reports the degree of improvement in durability that resulted.

It was not possible to compare the erosion rates of the various valve materials and designs. None of the reports provided erosion depth data, erosion velocity data, or solids concentration data. Service time ranged upward from 37 hrs. although the duty cycles were not described to any detail. Temperatures as high as 1400°F were involved. Conditions such as those involving pressure letdown are very difficult for conventional valve designs. Several reports have become available on valve material and valve design programs,[28-31] containing some very promising findings; these reports should be consulted for further details in this area. It is suggested that combinations of improved design (for example, several stages of pressure letdown rather than one; minimizing pressure drops across conventional valves) and improved erosion resistant materials could lead to improved valve service.

Recent reports on the erosion of valve materials[29-31] should be consulted for some results on hard surfaced materials for valve seats and other intervals.

3. Pumps

A total of 8 reports concerned with pump failures were examined. Severe particle erosion of the cast iron casings was a common finding. The other materials employed included high Cr irons principally in the centrifugal impellers. While the temperature of service was not particularly high, the solids concentration (gasifier fines in water) was reported as large as 20%. At the impeller tip speeds involved, this solids concentration provided considerable potential for rapid erosion of the casing as well as the impellers. Hard-face coatings were applied by welding in some cases to extend erosion life. Erosion depths on the casings ranged from 1/32 in. - 3/16 in. The service time reported varied from 4 hrs. to 1400 hrs. although the solids concentration was not noted and may have varied from less than 1% to as high as 20% due to process upsets. The high erosion rates appear to have involved erosion conditions considerably more severe than were originally anticipated. Several of the failures involved abrasive wear (rather than erosion) of the shaft seals due to solids trapped in the pump. Modifications in seal design to better accomodate higher-than-normal solids concentrations may be possible.

There were not sufficient data concerning service values of velocity, solids concentration, and erosion depth to permit quantitative conclusions to be drawn about specific materials or components of the pumps involved in the reported failures.

B. Hygas Facility[32]

1. Piping

There are 12 failure reports (see Table III) concerned with erosion of piping

components in the Hygas low BTU Ash Agglomerating Gasifier system. Two reports were concerned with transfer lines. In one case a blocked cross was severely eroded after 4 years of residence in the system transporting a 10% char in water slurry. Measurements of the eroded depth were not provided; however, this performance appears reasonable based on the indicated service. Clearly some regular replacement schedule is called for in char transport service; perhaps more erosion data on this example could provide quantitative input to assist in forecasting expected service life. Programs to ultrasonically monitor wall thickness during operation would be one approach. The second report concerned the erosion of an inner liner and subsequent erosion of a connection bellows. Few details are provided in the report; however, the potential always exists for misalignment or improperly fabricated joint structure. It is expected that joint discontinuities may sharply increase erosion over that expected for ideal conditions; hence, alignment is critical where erosion must be expected.

Two failure reports were concerned with pipe structures in or near the fluid bed in the gasifier. One report involved a carbon steel cooling pipe/ heat exchanger system operating at 800°F. Over a period of 1350 hours erosion reduced the pipe wall thickness sufficiently to permit the pressure to exceed the ultimate wall strength and burst the wall. Relatively few details were provided to permit further analysis.

Five reports were concerned with erosion within the internal cyclone separator. A summary of these experiences has been published.[33] The original design involved a single wall 310 stainless steel structure. After about 20 days, this wall (1/4 inch thick) was penetrated at the location of the entry stream impact. Upon repair, an erosion shield of RA330 stainless alloy (thickness 1/4 inch) was placed within the cyclone at the entrance flow impact site.

After 288 hours of further service, erosion penetrated the shield and wall (1/2 inch total). The erosion conditions were about 1000 lb/hr at a nominal velocity of about 90 ft/sec. The next modification involved welding onto the shell a liner of RA330 alloy that had been coated with a cobalt hardfacing. After 32 hours this liner failed near the weld joint; however, it was reported that this coated liner was considerably more erosion resistant than the uncoated liner. It was also noted that corrosion and the influence of corrosion scale on the erosion problem did not appear significant. The final disposition of this cyclone separator modification scheme is not known; however, proper installation (and positioning) of a suitable erosion-resistant liner would seem an appropriate strategy. Modest design changes to reduce the particle density in the flow by a larger impact area and to reduce the flow velocity by staging could also have a significant beneficial effect. One additional failure involved fracture of the cyclone-dipleg assembly due to stress caused by operation of the fluid bed at a raised level. Erosion of the dipleg occurred subsequent to the loss of proper position in the gasifier.

Three failures reported were concerned with a pressure tap tube and a thermowell tube located near and within the fluid bed.[34] The high exposure temperature (1700 to 2100°F) appeared to cause rapid (61 hrs) erosion/corrosion attack of the 310 stainless steel tubes even though the erosion velocity was relatively low, about 5 ft/sec.

2. Valves

There were no reported failures in valves due to erosion causes.

3. Pumps

One erosion report concerned a slurry pump that experienced rapid casing erosion in service that involved solids concentrations as high as 45%. Low pressure centrifugal pumps were employed that were of cast steel construction

with a plasma-sprayed hard coating. It was found that the coating rapidly flaked off under the erosive conditions present. Weld overlay of the critical parts with Stellite 12 coupled with a reduction in pump velocity by 50% was found to produce acceptable performance in this service.

C. CO_2 Acceptor Facility[35]

1. Piping

The Failure Information System contains 6 reports concerned with erosion failures of piping and related components (see Table III). A range of materials were involved including stainless steel alloys, nickel-based alloys, coatings and refractories . Two reports were concerned with acceptor lift line pipe experiencing excessive erosion at slip joints. The service involved temperatures of about 1400°F, erosion velocities of 55 ft/sec and an atmosphere of dolomite and gas. It was concluded that improper alignment of the pipe and the slip joint components can lead to increased erosion of the metallic liners. Design or installation procedure improvements should avoid such problems.

Two reports concerned an internal cyclone separator designed to remove fine particulates from the process gas. The wall material, type 316 stainless steel, eroded and in one report was penetrated at the location of flow impact from the inlet pipe. An erosion-resistant liner was noted as a recommended design change. In addition, it is suggested that the question of servicability should be examined so that cyclone maintenance can be routinely carried out by schedule.

Refractory liner erosion was experienced in one report concerned with the regenerator vessel. The impact area of gas, char and dolomite from an inlet line caused extensive erosion (about 13 in. deep) in the vessel wall refractory

liner. The importance of proper flow direction and the need to avoid limited areas of impingement are illustrated in this example.

2. Valves

One failure report was examined concerning valve erosion. The valve was used to handle dolomite and recycled gas at velocities of about 100 ft/sec. Severe erosion of an I800 alloy inner liner was found (a 1 inch by 3 inch section). The liner was apparently misaligned when installed leading to an unexpectedly rapid erosion situation. Neither the solids concentration nor the eroded depth were reported, preventing any quantitative conclusions concerning erosion rates in this situation.

3. Pumps

There were no erosion-related failures reported for pumps.

4. Other Information

An extensive review of the operating records of this facility has been carried out and reported.[35,36] A number of erosion problems were identified through this records study that did not appear in the Failure Information System. Relatively little detailed information on erosion parameters was available, however, so further analysis would be difficult. It was noted that significant problems faced during plant operation fell into five catagories: plugs, failures of materials and components, process related problems, coal preparation, and off site problems. Failures accounted for about 20% of total problems. Erosion was specifically mentioned in 24 instances of problems in this report.[35] A study of maintenance and operability records[36] included examination of pump and valve components performance. Further details beyond failure report information can be found in that source.

V. Summary and Recommendations

The purpose of this study was to examine the failure information available concerning erosion-related failures of selected components in three principal coal gasification systems. Examination of these records and other sources of information indicated that erosion was a serious problem in these systems. However, adjustments in response to those problems involving material design, components and system changes were for the most part successful and can probably be applied in future instances of related problems.

Many common problems were identified in spite of obvious differences in system characteristics.

- Piping components were prone to problems at joints and bends. Very careful alignment to avoid flow disturbances and low angle flow impact on metal walls is necessary. Reductions in solids concentration and flow velocity can be very effective in reducing erosion rates. These findings also apply to cyclone separator components where erosion opposite the inlet pipe was frequently a problem. Improved flow patterns within the cyclone should be an effective strategy, for example, exposing a larger area to first impacts (reduces particle density). Velocity reductions through the use of two or more stages can greatly reduce erosion due to the velocity dependence (V^2 to V^3) relation - although at a cost in separation efficiency.
- Valve components exhibited characteristic problems of liner erosion and closure failure leading to erosion. The existence of large pressure drops across valves (up to 1000 psig) placed a severe burden on most designs. It appears that other design approaches should be followed

for pressure letdown service (e.g. chokes). Hard facing materials application to valve seats and other internals is effective, although design changes and operating practices (with respect to solids contamination of the valve area) may be equally or more effective.

- Pump components also responded well to the use of hard coatings and overlays. It was noted that process upsets causing a significant increase in solids concentration presented to the pumps invariably led to serious problems. The tolerance of pump systems to 5 or 10 fold increases in solids concentrations is not large, particularly where seal and bearing wear enter as well as erosion. Pump speed reductions are an effective strategy in view of the power law velocity effect on erosion mentioned previously.

As indicated in Table III a minimum set of erosion-related information is needed to analyse erosion behavior. In all cases examined here, some critical information items were missing and prevented quantitative problem analysis. While it is appreciated that great difficulty exists in gathering such details "on the spot" in field situations, some improvements in information access can probably be accomplished in the future. The listing that follows is one suggestion of the needed items in priority order, i.e. the earlier listed items provide the most significant impact to subsequent problem analysis in quantitative terms.

1. Component description (geometry, sizes, etc.)
2. Material identification (alloy, coating, etc.)
3. Time in service (duty cycle, time of erosion, etc.)
4. Erosion velocity (maximum, average)
5. Erosion depth (maximum, area of erosion)
6. Solids concentration (maximum, average)

7. Environment (chemical, temperature)

8. Narative description of sequence of events

Even a partially complete set of information in each instance following these guidelines could permit a productive analysis of material erosion rates in service and provide valuable input to future materials, applications and component design developments.

Acknowledgments

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Table I. Failures due to Erosion and Other Causes

		Number of Items
All Causes:		485
Process:	CO_2 Acceptor	53
	Synthane	148
	Hygas	63
	Others	221
Erosion:		102 (21% all causes)
Process:	CO_2 Acceptor	7 (13%)
	Synthane	34 (23%)
	Hygas	13 (21%)
	Others	48 (22%)

Table II. Erosion-related Failure of System Components

	Number of Items	
All Causes:	485	
Erosion:	102	
Pumps		29
Valves		32
Piping		39
Other		13

(Note: Some reports involve more than one component)

TABLE III

EROSION INFORMATION SUMMARY

Failure Report #	Process	Component	Material	Time in Service (hrs)	Temp. of Service (°F)	Erosion Velocity (ft/s)	Solids Conc. (%)	Environment	Eroded Depth (in)	Details Summary
51	Synthane	Piping	Carbon moly steel	(6 mo)	to 900	NA	NA	Coal gas, char, steam	NA	Elbow, wall thickness penetrated where flow impacted; replaced with Tee.
57	"	"	Carbon steel (D2A)	(3 yr)	NA	NA	NA	Char, hot water, gases	NA	Elbow, corrosion/erosion of wall, not penetrated; replaced with 304 SS.
64	"	"	304 SS	(3 mo)	400	greater than 50	NA	Char, steam, coal gas	NA	Tee, wall thickness penetrated where flow impacted; replaced and lowered flow velocity.
68	"	"	304 SS	NA	800	NA	NA	Coal, steam, coal gas	1/16	Flange, gasket (flexitalic) eroded, 630 psig service, cone transport.
296	"	"	Carbon steel (D2A)	(1 wk)	NA	NA	NA	NA	NA	Elbow, wall thickness penetrated; welded on pad to repair.
382	"	"	(Steel ?)	(7 wk)	600	NA	NA	Char, steam	NA	Sleeve, inner, after pressure reduce valve, 600 psi to 10 psi; replace with ceramic.
385	"	"	Carbon steel	(6 mo)	300	NA	1 to 20	Char, hot water	~0.080	Elbow, above pump discharge where flow impacts.
398	"	"	1800	1000	800	NA	NA	Coal gas, dust, fine char.	~0.200	Cyclone, gasifier, wall thickness penetrated where flow impacted; install wear plate collars.

NA = not available

Failure Report #	Process	Component	Material	Time in Service (hrs)	Temp. of Service (°F)	Erosion Velocity (ft/s)	Solids Conc. (%)	Environment	Eroded Depth (in)	Details Summary
555	Synthane	Piping	Carbon steel (A105)	NA	540	NA	NA	Water, gas, coal fines	NA	Flange, flow directed at flange by off center orifice, gasket penetrated; aligned orifice.
565	"	"	316 SS, 1825	(9 mo)	NA	~100	NA	Coal dust, steam, coal gas	~0.220	Elbow, wall thickness penetrated where flow impacted; altered design.
9	"	Valve	Stellite	(14 mo)	300	NA	NA	Char	NA	Valve, level control.
90	"	"	Stellite 6	(18 mo) (37 hr run)	300	NA	NA	Char, water, coal gas	NA	Valve, gas let-down, erosion of body and trim.
120	"	"	Carbon steel, stainless steel	37	800	NA	NA	Char, water, gas	NA	Valve, erosion of trim and pipe, pressure let-down 600 psi.
216	"	"	Stainless steel sleeve ceramic trim	(2 mo)	NA	NA	NA	Char	NA	Valve, pressure let-down 1000 psi.
217	"	"	Stainless steel sleeve ceramic trim	(2 mo)	NA	NA	NA	Char	NA	Valve, choke for char let-down, WC trim evaluated.
253	"	"	NA	NA	300	NA	NA	Char, water, gas	NA	Valve, body wall penetrated.
254	"	"	Stainless steel	37	NA	NA	NA	NA	NA	Valve, let-down, 50% erosion of trim, erosion of pipe and flange.
465	"	"	WC trim, ceramic sleeve	300-400	NA	NA	NA	Char fines, steam	NA	Valve, steam vent, pressure let-down 600 psi.

Failure Report #	Process	Component	Material	Time in Service (hrs)	Temp. of Service (°F)	Erosion Velocity (ft/s)	Solids Conc. (%)	Environment	Eroded Depth (in)	Details Summary
513	Synthane	Valve	Carbon steel	(6 mo)	NA	NA	NA	Char, water, steam, coal gas	NA	Valve, gate and body eroded.
522	"	"	Cast steel alloy	(1 yr)	300	NA	NA	Char and coal dust, water	NA	Valve, scrubber recycle, plug eroded.
530	"	"	Cast stainless alloy (HK40), Hasteloy C	(2 yrs)	1400	NA	NA	Steam	NA	Valve, safety, pressure relief 1160 psi, disc eroded.
590	"	"	Ceramic (C 999)	(4 days)	NA	NA	NA	Char, hot water, gases	NA	Valve, choke plate, holes in trim penetrated wall.
133	"	Pump	NA	(2 mo)	200	NA	NA	Char, water	NA	Pump seal, eroded, motor seized.
147	"	"	Cast Cr-iron, Ni-hard casing	1200	80	NA	NA	Char, water	NA	Pump casing, wall thickness penetrated, 1/2 in. diameter hole.
166	"	"	Cast Cr-iron, Ni-hard casing	300 slurry 600 water	80	NA	NA	Char, water	NA	Pump casing, wall eroded through thickness.
167	"	"	Cast iron impeller, steel case	450	200	NA	NA	Water, coal slurry	1/10	Pump casing erosion, wear ring erosion (.100 in.).
259	"	"	Cast iron, Cr steel wear parts	(1 1/2 yr)	100 to 300	NA	NA	Char, water	NA	Pump, recirculating, seals worn.
383	"	"	NA	NA	125	NA	1 to 20	Char, hot water	NA	Pump seals, eroded by char, repair with plastic packing.
564	"	"	Cast iron	1422	NA	NA	NA	Char, water	1/8 to 3/8	Erosion of casing (3/16 in.), head (3/8 in.), wear ring (1/8 in.)

Failure Report #	Process	Component	Material	Time in Service (hrs)	Temp. of Service (°F)	Erosion Velocity (ft/s)	Solids Conc. (%)	Environment	Eroded Depth (in)	Details Summary
589	Synthane	Pump	Cast Iron	4	300	NA	NA	Char, water, coal gas	1/32	Pump casing eroded, seal an[d] bearing failure.
12	Hygas	Piping	Steel (A105)	(4 yrs)	200-300	(30 gal/min)	10	Char, water	NA	Blocked cross, char slurry transport line, severely eroded.
206	"	"	Steel (SA106)	1350	800	0.5	(fluid bed)	Coal, air	NA	Cooling pipes, erosion thinned wall causing ruptur[e]
210	"	"	NA	NA	NA	NA	NA	Coal, gas	NA	Bellows, transfer line, in[ner] liner failed causing erosi[on] of bellows.
468	"	"	310 SS	(20 days)	to 1800	120-160	NA	Coal fines, gas, steam	0.250	Cyclone, wall thickness pen[e]trated where flow impacted.
515	"	"	310 SS, liner RA330 alloy	288	to 1700	75-90	(1000 lb/hr)	Coal gas, coal fines	NA (0.500)	Cyclone, wall and liner thickness penetrated where flow impacted.
517	"	"	310 SS, liner RA330, cobalt alloy coating	32	to 1700	75-90	(1000 lb/hr)	Coal gas, coal fines	NA	Cyclone, severe erosion of 0.25 in. liner and coating.
560	"	"	310 SS, SS liner RA330, cobalt alloy coating	32	to 1700	75-90	(1000 lb/hr)	Coal gas, coal fines	0.500	Cyclone, summary of reports #515, 517, weld on liner failed.
575	"	"	310 SS	[illegible]40	to 1850	NA	(fluid bed)	Coal, gas, steam	NA	Cyclone dipleg, pressure tap, details of reports #578, 579.
578	"	"	310 SS	61	1750	5	(fluid bed)	Coal, gas, steam	NA	Dipleg, internal cyclone, fell into bed and eroded.
579	"	"	310 SS	61	1750	5	(fluid bed)	Coal, gas, steam	NA	Tube, pressure tap, surface erosion in bed.

Failure Report #	Process	Component	Material	Time in Service (hrs)	Temp. of Service (°F)	Erosion Velocity (ft/s)	Solids Conc. (%)	Environment	Eroded Depth (in)	Details Summary
580	Hygas	Piping	310 SS	61	1700	5	(fluid bed)	Coal, gas, steam	NA	Tube, thermowell, immersed in fluid bed.
598	"	"	310 SS	61	to 2100	5	(fluid bed)	Coal, gas, steam	0.090	Tube, pressure tap, erosion and corrosion in bed.
42	"	Pump	Cast steel, coated	NA	NA	NA	to 45	Coal slurry, oil	NA	Pumps, slurry feed, rapid erosion, changed to Ni hard coatings, Stellite 12.
127	CO_2	Piping	1800 carbon steel, varioos hard facings	(2 1/2 yr)	NA	NA	NA	Dolomite, gas	NA	Acceptor lift line pipe, erosion at slip joint.
132	"	"	310 SS, stellite coating	630	1450	55	NA	Dolomite, coal gas	NA	Acceptor lift line pipe, erosion at slip joint cones, pipe wall penetrated.
247	"	"	Refractory, superex, castables	NA	to 2600	NA	NA	Hot gas, char, dolomite	13	Regenerator vessel, erosion of refractory lining opposite gas inlet line.
263	"	"	NA	NA	NA	NA	NA	NA	NA	Cyclone separator, recommend abrasion resistant liner.
290	"	"	NA	13,000	1830	NA	NA	Flue gas	NA	Pipe, flue outlet, erosion and combustion.
474	"	"	316 SS	(629 days)	to 550	to 90	NA	Char, coal gas	0.322	Cyclone separator, wall thickness penetrated at flow impact area.
117	"	Valve	1800	(9 mo)	1450	to 100	NA	Dolomite, recycled gas	NA	Valve, liner, misaligned and eroded.

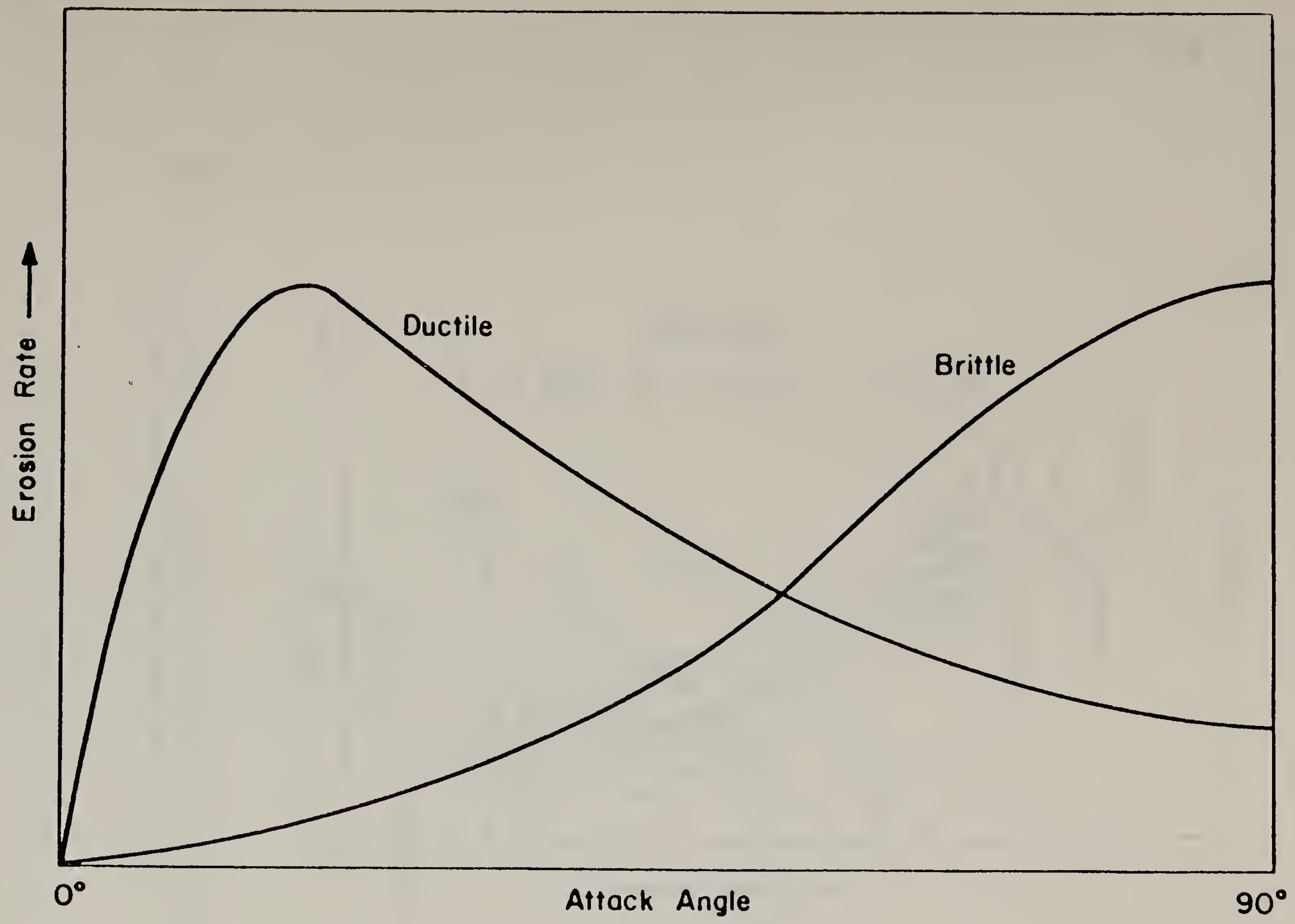

Fig. 1. Schematic representation of erosion rate vs attack angle.

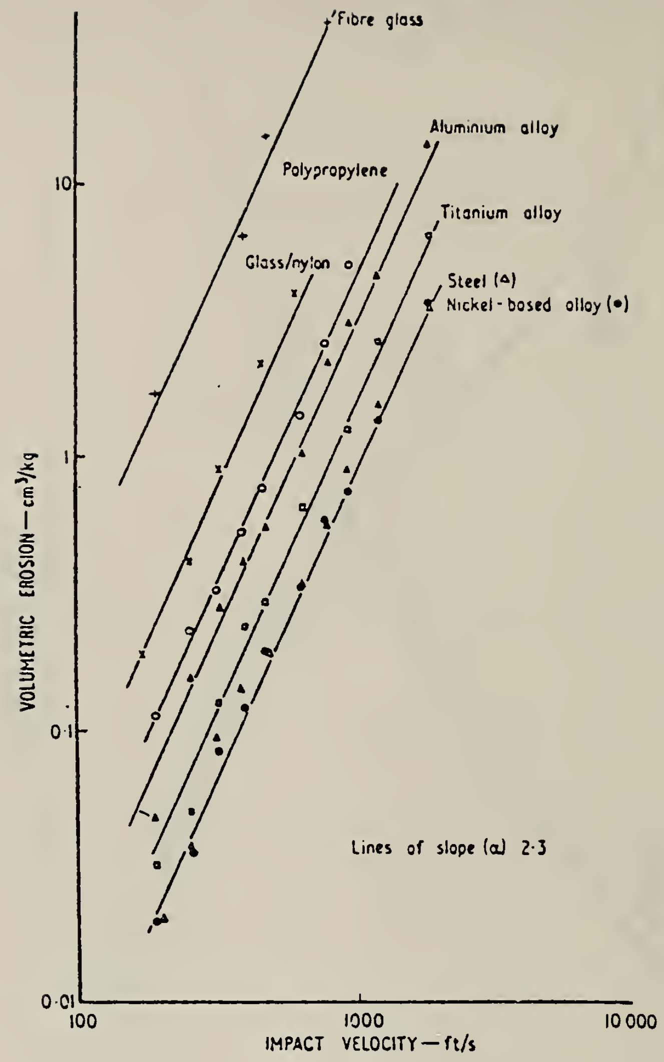

Fig. 2. Influence of velocity on erosion for different materials.[15]

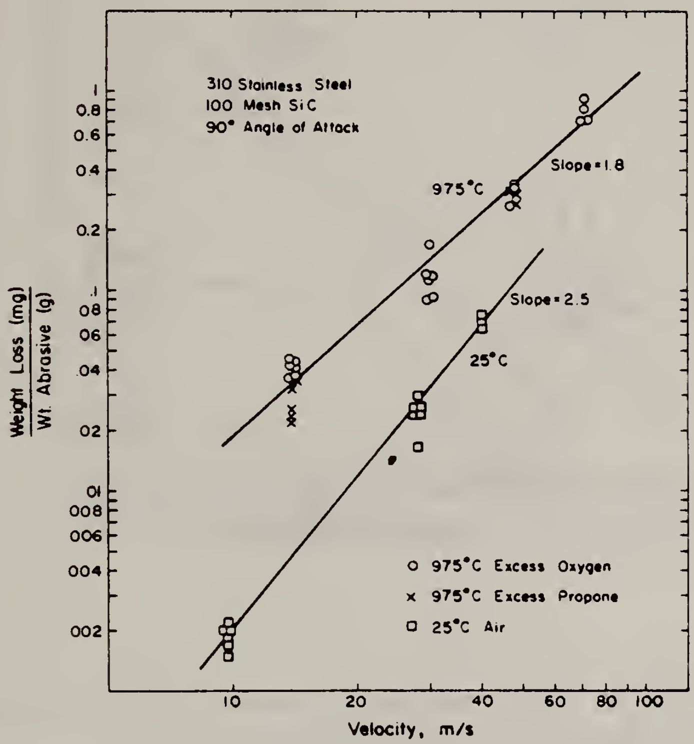

Fig. 3. Velocity dependence of erosion of stainless steel at 975°C and 25°C.[11]

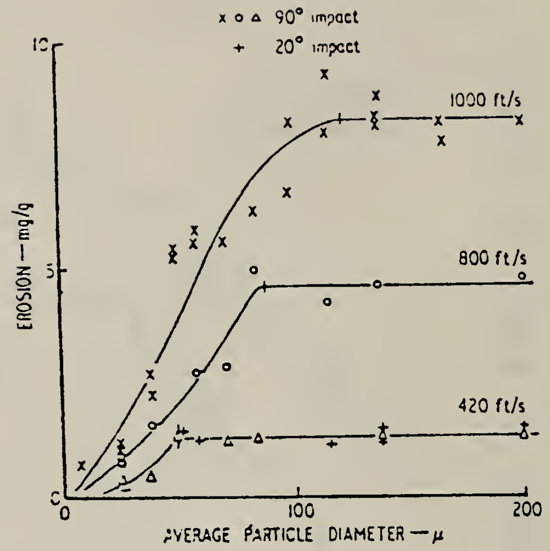

Fig. 4. Influence of particle size on erosion of an 11 percent chromium steel.[15]

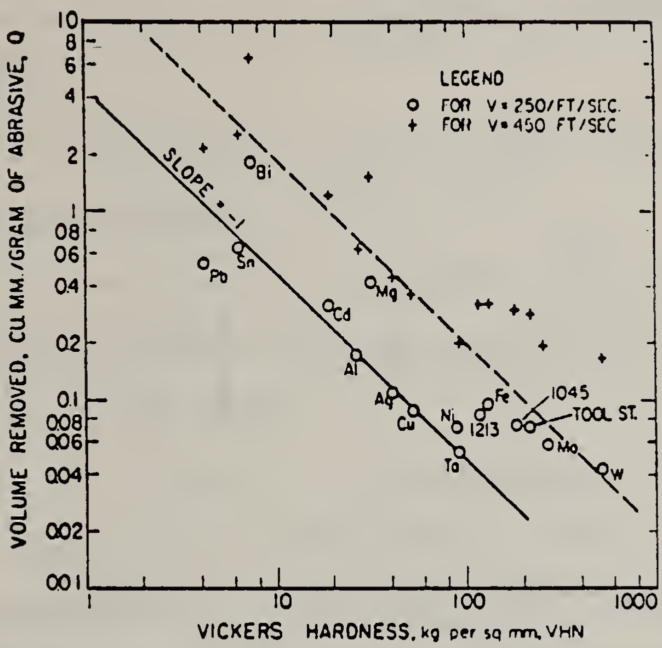

Fig. 5. Volume removal as a function of hardness (VHN) for metals eroded at $\alpha=20$ deg and velocities of 250 and 450 ft/sec. (No data were taken for nickel at 450 ft/sec.) All metals except cadmium were in annealed condition.[6]

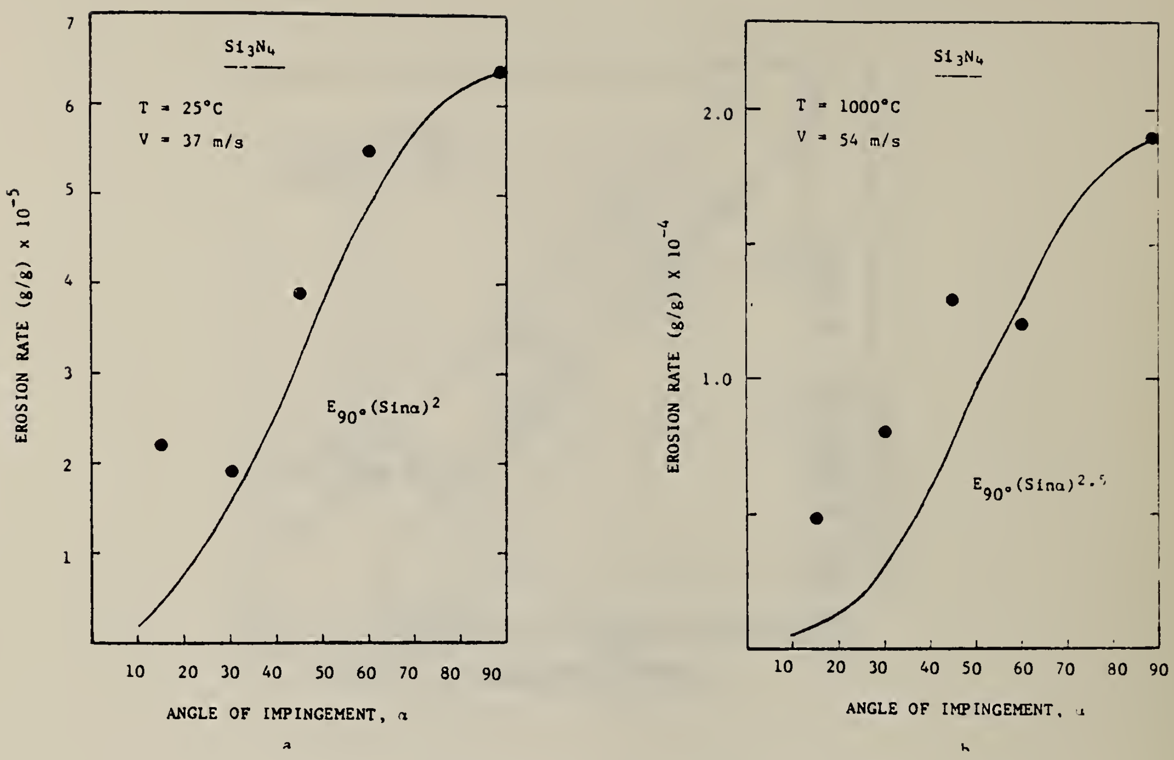

Fig. 6. Erosive wear of hot-pressed silicon nitride as a function of impingement angle. Curves represent erosion dependence for purely brittle behavior.[21]

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16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

Failure information reports concerning erosion that are contained in the NBS-DOE Failure Information Center have been analyzed for the purpose of identifying critical and common factors associated with erosion in coal gasification applications. Emphasis was placed on the components most frequently identified in erosion failure reports - piping, valves, pumps, cyclones - and on three of the principal processes. Recommendations are presented on a minimum set of erosion-related information needed to analyze erosion behavior. A brief review of solid particle erosion and several bibliographic references are also included.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Cyclones; energy; erosion; metals; pumps; valves; wear.

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